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# Nano-scale hot wire sensors for turbulence measurement applications

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**Abstract**

In this paper hot wire sensors for turbulence measurement were developed, which mainly consisted of free-standing nano-scale platinum wires. Specific spatial 3D arrangements of these sensors enable measurements of quantities of small turbulence structures, such as velocity, shear stress and vorticity, in the three dimensions. To decrease the filter effect at moderate and high intensity of turbulence, more over, to detect small structure in the turbulent flow, the characteristic size of the sensor was minimized to 260nm. TCR (temperature coefficient of resistance) of the sensors are characterized and reached typically 0.217 %/K.



*Keywords*: Hot wire, Platinum, 3D turbulence measurement, Shear stress, Vorticity

## 1. Introduction

The measurement of velocity, shear stress, and vorticity is very important to investigate the physical properties of turbulent flow. A hot wire sensor as a conventional apparatus has been widely used to detect the velocity field of the turbulent flow [1]. However, limited by the structural size, traditional hot wire sensors can not detect significant quantities of velocity, shear stress and vorticity in the tiny turbulence structures smaller than the hot wires' sizes [2]. The sizes of the interesting turbulence structures can usually go down to very small scale, such as Kolmogorov micro scale. Typical value of this scale for atmospheric turbulence is in the range from 0.1-10 mm. Due to more thermal inertia, which is also related to the dimensions of the hot wire, the conventional sensors filter the significant high frequency components of turbulence. Especially for moderate and high intensity turbulences, the velocity fluctuations are quite fast. Therefore, it is essential for accurate and comprehensive measurements to

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reduce the size of the hot wire as small as possible. In this paper, shear stress and vorticity are decomposed to the more explicate quantities. These quantities can be measured by the hot wire principle. We combined spatial structures of several hot wire sensors to measure these quantities. The essential part of the structures, the single hot wire sensor, is fabricated by the MEMS process.

## 2. Hot wire sensor principle and design

### 2.1. Hot wire principle

The heat lost rate of the hot wire sensor, placed in the flow, depends on the velocity of the flow. The heating wire' temperature is determined by the thermal equilibrium between Joule heating and heat loss in the flow. At the same time, the wire has a temperature-resistance effect that means its resistance is varied with the temperature. The wire's resistance is related to heating current and flow velocity, therefore voltages drop on the wire is also related to the flow velocity. King [3] concluded the relation as followed:

$$U^2 = A + BV_{flow}^n \; (n \approx 0.5, A, B \text{ are empirical calibration constant for each fluid}) \tag{1}$$

Hot wire is not only sensitive to the magnitude of velocity but also to the flow directions, as illustrated in figure 1. Jørgensen took account of the velocity angle and its magnitude, and proposed a new concept of effective cooling velocity [4]:

$$V_{effective}^2 = V_N^2 + kV_T^2 + hV_B^2 \; (k, h \text{ are constants related to structure of hot wire. } k \approx 1, \; h \approx 0) \tag{2}$$

### 2.2. 3D velocity measurement

Figure 2 shows the structure, which is used to measure $V_i$. It has three pairwise orthogonal hot wire sensors. These wires can be placed in the turbulent flow and simultaneously measure the magnitude and angle of turbulence velocity. Applying Equation (2) on every hot wire we obtain Equation (3):

$$\begin{cases} V_{wire1}^2 = (V_x \cos 45° + V_y \cos 45°)^2 + kV_z^2 + h(V_x \sin 45° - V_y \sin 45°)^2 \\ V_{wire2}^2 = V_y^2 + kV_x^2 + hV_z^2 \\ V_{wire3}^2 = V_x^2 + kV_y^2 + hV_z^2 \end{cases} \tag{3}$$

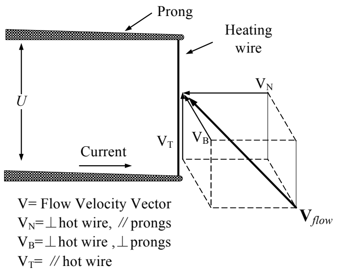


Fig. 1. Hot wire measurement principle

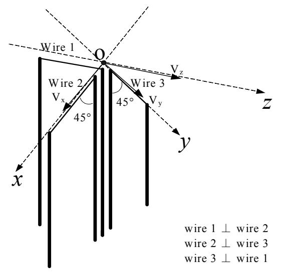


Fig. 2. Three pair-wise orthogonal hot wires for 3D velocity measurement

### 2.3. Shear stress and vorticity measurement of hot wire

To measure the components of shear stress and vorticity, they are deduced and simplified as in the equation (4) and equation (5). Using the $\Delta V_i/\Delta j$ enable the calculation of the shear stress and vorticity.

$$\text{Shear stress: } \tau = \mu \frac{\partial V_x}{\partial y} \approx \mu \frac{\Delta V_x}{\Delta y} \quad (\mu \text{ is dynamic viscosity of fluid}) \tag{4}$$

$$\text{Vorticity: } \omega = \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} \frac{\partial V_z}{\partial y} - \frac{\partial V_y}{\partial z} \\ \frac{\partial V_x}{\partial z} - \frac{\partial V_z}{\partial x} \\ \frac{\partial V_y}{\partial x} - \frac{\partial V_x}{\partial y} \end{bmatrix} \approx \begin{bmatrix} \frac{\Delta V_z}{\Delta y} - \frac{\Delta V_y}{\Delta z} \\ \frac{\Delta V_x}{\Delta z} - \frac{\Delta V_z}{\Delta x} \\ \frac{\Delta V_y}{\Delta x} - \frac{\partial V_x}{\Delta y} \end{bmatrix} \tag{5}$$

For measuring $\Delta \boldsymbol{V}_i/\Delta j$, structures as shown in the figure 3 and figure 4 are designed. 1D shear stress can be determined by the ratio of the velocity difference of main flow to the distance between two paralleled hot wires along $y$-axis (figure 3). The structure as shown in figure 4 can measure velocity gradient and 3D vorticity. There are three groups of hot wire sensors. Each group has the same structure as shown in figure 2. Using Equation (3), $\boldsymbol{V}_i$ is determined. $\Delta \boldsymbol{V}_i/\Delta x$ and $\Delta \boldsymbol{V}_i/\Delta y$ are approximately equal to the ratio of velocity difference between every two detected points to their intervals along $x$-axis and $y$-axis. $\Delta \boldsymbol{V}_i/\Delta z$ can be calculated by Taylor's frozen-flow hypothesis [5]:

$$\frac{\partial V_x}{\partial z} = -\frac{1}{\overline{V}}\frac{\partial V_x}{\partial t} \approx -\frac{1}{\overline{V}}\frac{\Delta V_x}{\Delta t}, \quad \frac{\partial V_y}{\partial z} = -\frac{1}{\overline{V}}\frac{\partial V_y}{\partial t} \approx -\frac{1}{\overline{V}}\frac{\Delta V_y}{\Delta t} \; (\overline{V}\text{, local mean velocity along the streamwise direction}) \tag{6}$$

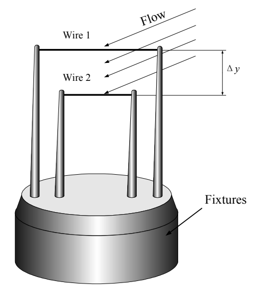


Fig.3. Two paralleled hot wire for 1D shear stress measurement

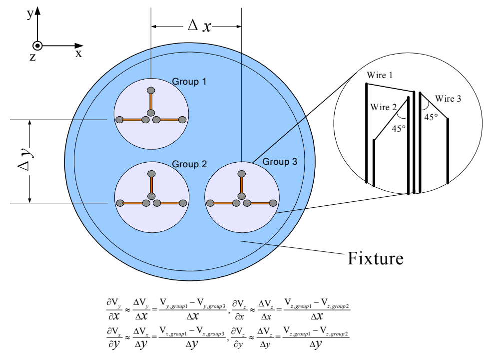


Fig.4.Three groups of hot wire sensors for velocity gradient measurement

## 3. Sensor fabrication

To reduce the size and decrease the fabrication cost, a general structure is designed. Every hot wire sensor for the different purposes has a similar structure, as shown in the figure 5. Therefore, they can be fabricated within the same process. The fabrication flow of a single hot wire sensor is presented in figure 6. It is made by a micro fabrication process. It has three layers, consisting of a platinum layer for sensing temperature variation on the top, a WTi layer as a sacrificial layer and barrier layer, and an electro conductive layer to increase signal-noise ratio.

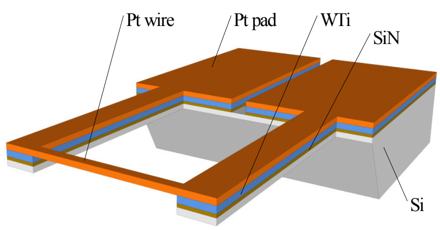


Fig.5. Structure of single hot wire sensor

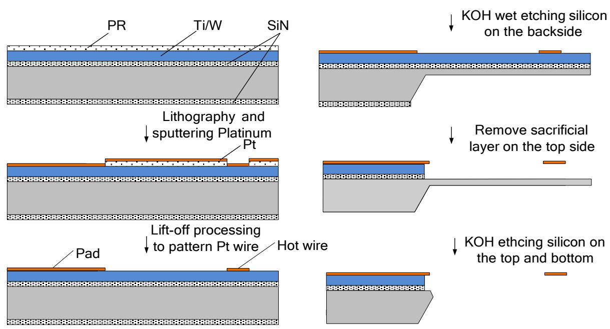


Fig.6. Process flow of single hot wire sensor

## 4. Result and discussion

Hot wire sensor, as the key component for these quantities' measurement, was fabricated as shown in figure 7. The size of the Pt wire is 260nm×3.36μm×460μm, and it is demonstrated that this nano-scale Pt wire is robust enough to withstand the atmosphere and air flow. Investigations on the TCR performance of hot wire sensors are carried out in a temperature controlled chamber. The result is illustrated in figure 8. It shows the linear relation of temperature to the resistances of hot wire sensor. The TCR reached to 0.217%/K which is marginally lower than the well known value for pure bulk Pt of 0.385 %/K.

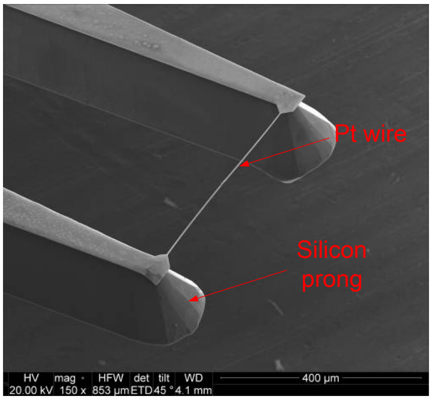

Fig.7. SEM image of a fabricated hot wire sensor.

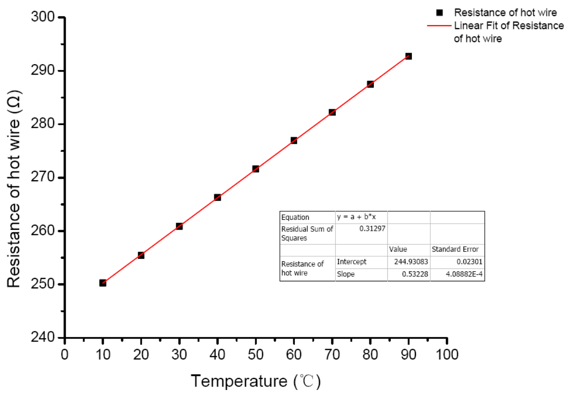

Fig.8. The relation between resistances of hot wire sensors and temperature

## 5. Conclusion

Shear stress and vorticity of turbulent flow are deduced into simple quantities which related to components of velocity and their gradients. In this work, specific structures of several hot wires sensors are designed to obtain components of velocity and their gradients, which allow calculating shear stress and vorticity. These hot wires were fabricated by MEMS process. A nano scale hot wire was developed and prototyped which has a characteristic size of 260nm, and its TCR reached 0.217%/K.

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